UDC 551.543.4:551.583.13(100-17)"32"

LONG-PERIOD VARIATIONS IN SEASONAL SEA-LEVEL PRESSURE OVER THE NORTHERN HEMISPHERE [1]

A. JAMES WAGNER

Extended Forecast Division, U.S. Weather Service, NOAA, Suitland, Md.

ABSTRACT

The standardized departures of sea-level pressure from the normal over the Northern Hemisphere for each of the four seasons were examined by means of spectrum analysis. Emphasis was placed on interpreting the geographical distribution of relative spectral power at different periods, rather than the power distribution within the individual spectra.

The predominant characteristic of the data was trend, found to represent real meteorological effects and not spurious results of changes in station locations or times of observation. Particularly in subtropical latitudes where the trend was greatest, the data were characterized by large 1- and 2-year-lag autocorrelations and pronounced "red noise" spectra. Exceptionally large 2-year-lag autocorrelation coefficients over several extensive regions of the hemisphere were related to marked departures of the data series from a linear first-order Markov process in those areas.

Although not so strong in an absolute sense as the trend, several moderately strong quasi-periodicities were found that appeared to be related to specific geographical or climatological features. The seasonal sea-level pressure data from arid and semiarid regions in widely separated parts of the hemisphere displayed a rather strong peak of spectral power in the band centered near 21 yr.

Data from an extensive area of the northern Pacific Ocean showed a broad spectral peak in the range of 5 to 6 yr, particularly in winter and summer. A pronounced spectral peak in the vicinity of 2½ yr was observed in the data series for winter over the Gulf of Alaska, the Mediterranean, and to a lesser extent off the east coast of the United States. All these areas are characterized by frequent and often intense cyclogenesis during the colder months.

Although the large amount of trend in the data made if difficult to determine the significance of individual spectral peaks, the quasi-beinnial oscillation also appeared to be a real characteristic of the data. A moderate peak was observed in the spectrum of the data series for some subtropical and continental high-pressure areas, particularly in winter. A preponderance of the spectra at the individual Northern Hemisphere grid points displayed relative peaks in the range of 26 to 28 mo, most markedly for the winter data.

CONTENTS

1. INTRODUCTION

Due to the recent interest in the puzzling phenomenon of the quasi-biennial oscillation (QBO), an investigation was undertaken to see whether this effect could be detected in seasonal mean sea level pressure over the Northern Hemisphere. Other investigators had found evidence of the QBO in surface parameters at certain stations with fairly long and reliable periods of record (Landsberg et al. 1963), and evidence for the QBO from tropospheric and stratospheric variables had become practically indisputable (Reed 1965).

The standardized departure from the normal (SDN) of seasonal sea-level pressure data at 226 grid points over the Northern Hemisphere for 66 yr beginning in 1899 were examined by means of spectrum analysis. Evidence for the QBO was found, but the presence of other quasi-periodicities and in particular the large amount of trend and consequent "red noise" in the spectra at most of the data points hindered the finding of a definitive result on the QBO.

The geographical distribution of power in some of the spectral bands, including the QBO range, was found to be of considerable interest and was related to the synoptic climatology of large-scale weather features during the four seasons.

2. DATA AND COMPUTATIONAL PROCEDURE

The data used in this investigation were obtained from the U.S. Weather Bureau (1943*a*) original historical weather map series of 1899–1939 and subsequently from the continued historical series and from unpublished monthly mean maps furnished by the Extended Forecast Division of the U.S. Weather Service at Suitland, Md. Mean values of sea-level pressure for each of the four seasons were obtained from the daily and monthly mean maps for the 66-yr period from 1899 through 1964 at each

[1] This paper is based largely on research done while the author was a graduate student at the Massachusetts Institute of Technology at Cambridge. The computations and spectrum analyses were done on the IBM 7094 at the MIT Computation Center.

of 226 grid points located at longitude-latitude intersections in the Northern Hemisphere. Data for the 36 points comprising the 10°N latitude belt were available from only the original 40-yr historical series. Other than that, except for certain portions of the Eastern Hemisphere where the observations were interrupted by wars, the completeness of the record was good to excellent. The program used to do the analysis kept track of the number of pairs of years that had data available to compute the lag autocorrelations at each grid point. The normals used in this study were obtained from the U.S. Weather Bureau (1952) series of normal monthly mean charts in the Northern Hemisphere.

To show the four seasons in proper perspective, we placed the data into standardized form. The SDN was computed by dividing the departure from normal by the mean standard deviation at each of the grid points. Willett (1965) has discussed the advantages of using standardized data, especially in statistical studies. The use of ordinary climatic data covering different geographical areas and seasons results in apparently greater and more significant effects at high latitudes and during the seasons of greater atmospheric variability thereby distorting the relative importance of effects when different areas or seasons are compared.

The statistical processing of the data consisted of computing the lag autocorrelations for lags of 1 to 21 yr and the power spectrum of the variance for each data point and season. The procedure used is basically that outlined in chapter 6 of Panofsky and Brier's book (1958). The results of the spectrum analyses were smoothed by "hanning" or averaging each "raw" spectral coefficient with its immediate neighbors by the weights 1:2:1. The first and last coefficients on the ends of the spectrum were smoothed by a simple average with their respective adjacent coefficients.

The choice of 21 yr for the maximum lag autocorrelation used to compute the spectrum analyses was determined by what was felt to be the best possible compromise between reliability of the individual coefficients and resolution, resulting in slightly over six degrees of freedom. The selection of 21 yr for maximum lag also fixed some of the spectral coefficients at periods of 21 yr, 10.5 yr, and 26.5 mo, corresponding closely to the mean lengths of the double and single sunspot cycles and the QBO. The coefficient corresponding to the double sunspot cycle was thus separated from the trend by one other coefficient, an important consideration when a large amount of variance in the trend may result in "leakage" into the longer period coefficients. (See the discussion of leakage problems in chapter 8 of the text by Granger and Hatanaka 1964.) Also, because of the way the hanning was done on the ends of the spectrum, it was wise to separate the quasi-biennial period from the end period of 2.0 yr by one other coefficient.

Each season was processed separately, rather than using four-season running averages to remove annual effects from the whole data sample analyzed as one. There were two reasons for analyzing the seasons separately: (1) The relative importance of the spectral power at any given period could be compared in different seasons, and (2) the use of a "running mean" type of filter on a data series to be subject to spectrum analysis will result in spurious periodicities and even phase reversals at some frequencies as shown by Holloway (1958).

3. RESULTS AND DISCUSSION

THE 1- AND 2-YEAR-LAG AUTOCORRELATIONS

The single most obvious result revealed by the analysis performed in this investigation was that the outstanding characteristic of the data at most of the grid points was trend. Before examining this and the other periods in detail, however, we shall examine the hemispheric distribution of the lag autocorrelations for 1 and 2 yr displayed in figures 1 and 2, respectively.

The actual number of years of data available at each point was considered in estimating the significance of the correlations. The significance was determined from table A–30a in Dixon and Massey's text (1957), using the two-tailed assumption since the yearly lag correlations can be both positive and negative. Due to the varying number of years with missing data in different parts of the hemisphere, the analyzed lines in figures 1 and 2 do not coincide necessarily with equal numerical values of the correlation, but are actually isopleths of significance level.

It can be seen that over much of the Northern Hemisphere at low latitudes, the lag autocorrelations of sea-level pressure standard deviation ratio for 1 and 2 yr are significantly positive at better than the 1-percent level. Altogether, over the whole hemisphere, there are at least 37 points with 1- and 2-year-lag autocorrelations exceeding the 1-percent singificance level during each of the four seasons, whereas only two or three would be expected by chance if the data at each point are independent of the others. Even allowing for the fact that the data are not completely independent in space, it is believed the areas covered by significant correlations far exceed those that would be expected by chance.

The most extensive areas of highest correlation appear to coincide with the subtropical high-pressure belts over the oceans and with the great monsoonal circulation centers at low-latitudes over Asia. Smaller areas of significantly high 1- and 2-year-lag autocorrelations are found over the Caribbean, Mexico, and the southwestern United States, as well as in the vicinity of the Arctic Basin.

Namias (1954, 1960) has previously found statistical evidence that in general the 700-mb height is most persistent both on a month-to-month and season-to-season basis in the areas of subtropical high pressure. Thus, it would appear that there is a decided tendency for these high-pressure belts to be characterized by high persistence both at the surface and aloft on all time scales of atmospheric

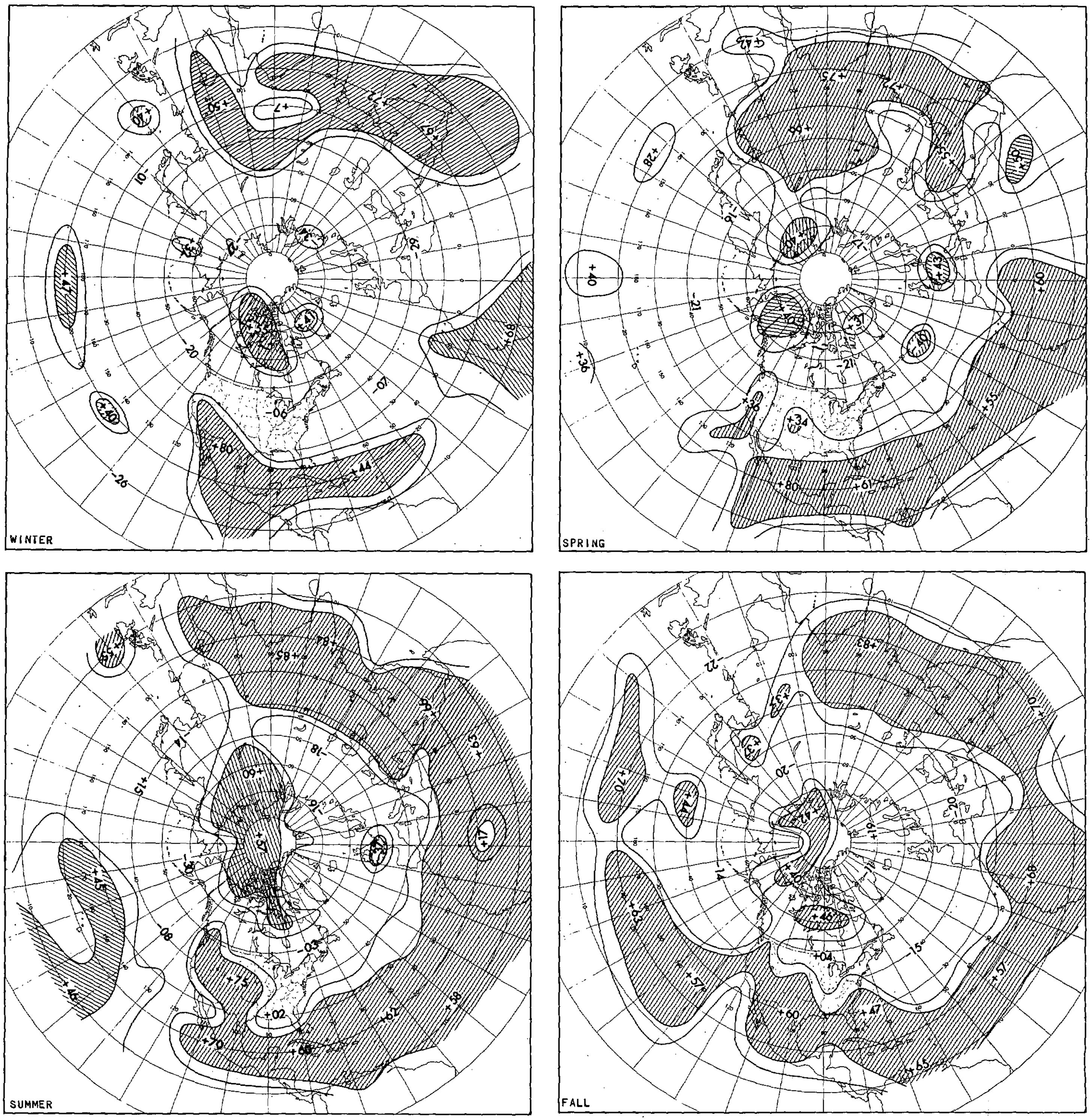

FIGURE 1.—The 1-year-lag correlation, (r_1) in hundredths, of standardized departure of sea-level pressure from normal for the four seasons. The heavy lines enclose areas where the correlations are significant at more than the 5-percent level. Areas with correlations of more than the 1-percent significance level are also shaded. Maximum and minimum values are labeled in hundredths.

motion from daily (as is well known) to seasonal averages in successive years. The local 700-mb height and surface pressure are positively correlated rather strongly with each other in the predominantly barotropic subtropical regions.

There were only two points each on the spring and summer maps and none on the fall or winter maps that had negative 1-year-lag autocorrelations of 1-percent or higher significance, and there were no points with 2-year-lag autocorrelations of this signfiicance during any season.

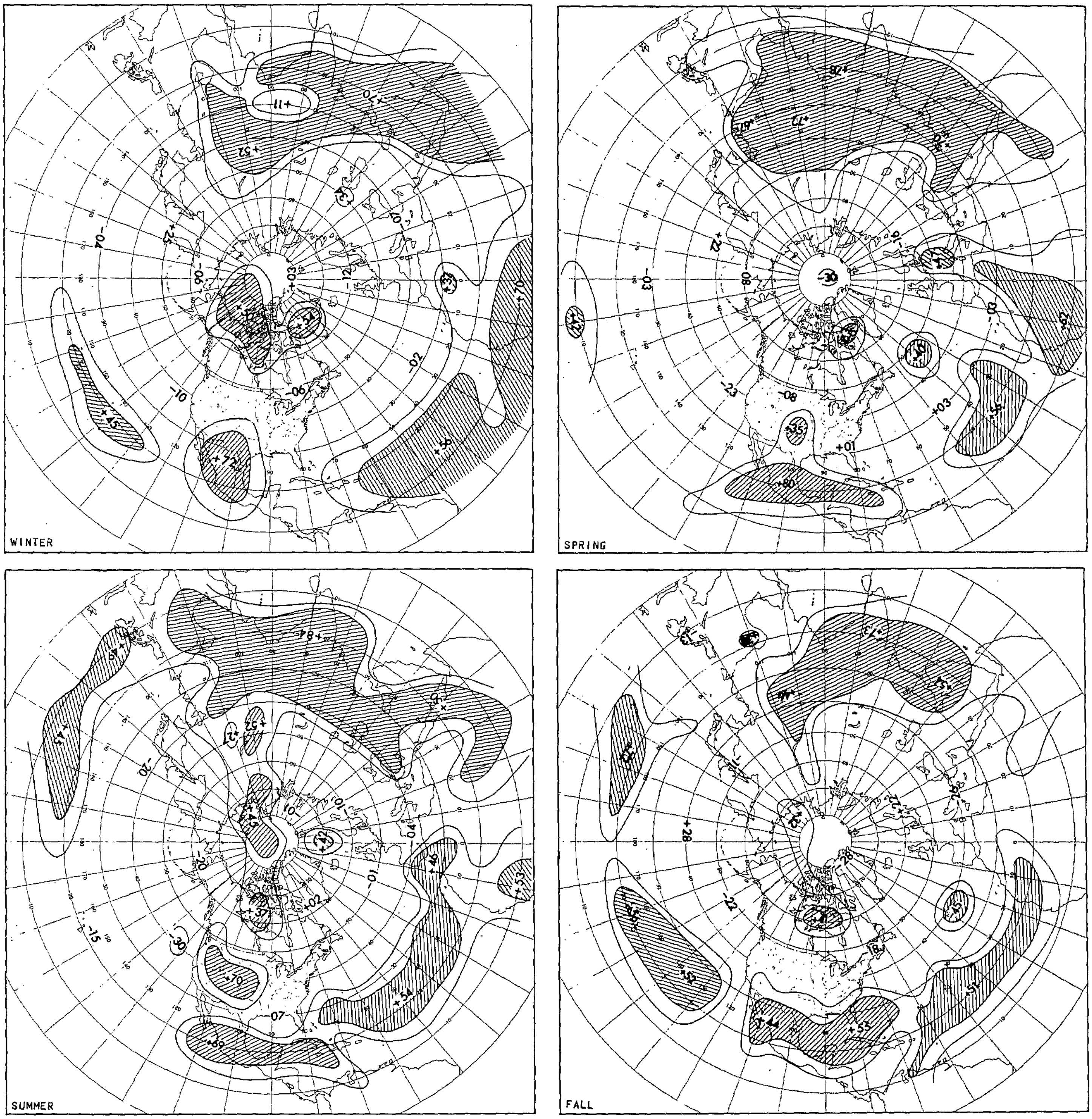

FIGURE 2.—Same as figure 1, except for the 2-year-lag correlation, (r_2).

It is impossible to compare the two points in the central North Atlantic Ocean on the spring map with any weather records, but the significant negative 1-year-lag autocorrelations at the two points near the southern British Isles agree very well with the findings of Wright (1968) and Davis (1968) of strong yearly alternations of summer temperature and other meteorological parameters over southern Britain and adjacent parts of continental Europe. Temperature is correlated positively with pressure during the summer in these areas, as high pressure is associated with anticyclonic conditions, subsidence, and generous sunshine, while low pressure and cyclonic activity generally favor rainy and cool weather.

It is possible to derive a rather interesting parameter from the 1- and 2-year-lag correlations. Time series of geophysical data generally display a red noise spectrum, meaning that much of the power in the spectrum is concentrated at the low frequencies or long periods. The amount by which the power shifts to the low-frequency end of the spectrum is proportional, more or less, to the autocorrelation at lag 1. An estimated red noise spectrum may be computed from the autocorrelation at lag 1, on the assumption that the data series follows a linear first-order Markov process, which means that each successive value in the series could be expressed by the autocorrelation at lag 1 times the previous value plus a random component (Gilman et al. 1963 and Mitchell 1964).

However, the series of seasonal sea-level pressure standardized deviations analyzed in this article departed considerably at many locations from the idealized linear first-order Markov process. This departure can be estimated by the quantity $(r_2-r_1^2)/(1-r_1^2)$ where r_1 and r_2 are the lag autocorrelations at 1 and 2 yr, respectively. The closer this quantity is to zero, the nearer the data series is to a linear first-order Markov process. A positive value of the quantity means that the future value of the seasonal mean sea level pressure is correlated more positively, on the average, with the value 2 yr previously than an exponential decrease from the 1-year-lag autocorrelation would imply. The reverse is true for negative values.

Maps of the hemispheric distribution of $(r_2-r_1^2)/(1-r_1^2)$ for the four seasons are shown in figure 3. It can be seen from the many positive areas that rather extensive parts of the hemisphere have a higher persistence of seasonal sea-level pressure anomaly at lags longer than 1 yr than would be implied by a linear first-order Markov process.

These areas are often the same as those having high autocorrelations at both 1- and 2-yr lags, particularly the latter (compare fig. 3 with figs. 1 and 2). As will be seen in this paper, many of these are also locations where the quasi-biennial oscillation is fairly well defined at a period close to 24 mo. This relationship with the QBO might be expected because the numerator of the quantity is $r_2-r_1^2$. A relatively large value of r_2 does not imply, in itself, a strong biennial component. When r_1 and r_2 both have large positive values, there is usually a considerable amount of trend in the data.

A possible physical interpretation of high positive values of $r_2-r_1^2$ is that the atmosphere "remembers" or is influenced by conditions further back than in the immediate past. Storage of heat in deeper layers of the ocean is a process that might influence the atmosphere in this manner, as suggested by Mitchell (1966) and Namias (1969). The possible influence of this type of process appears to be limited to rather low latitudes over the oceans as seen from figure 3, and it is difficult to explain the areas over the continents in this manner. The most marked area of large positive values of $r_2-r_1^2$ is found over Asia south of 40°N in spring. Perhaps there is a strong tendency for springs with early or late monsoons to occur in groups of several consecutive years, due to some other type of sea-air or even land-air interaction.

TREND AND LONGER PERIOD VARIATIONS

As mentioned previously, trend was the predominant characteristic of the 66-yr sea-level pressure data series at a large proportion of the Northern Hemisphere grid points, especially at low latitudes. For instance, at points along 20°N in the Western Hemisphere, trend accounted for over 25 percent of the variance in the power spectra during nearly all seasons.

The amount of trend in the standardized data tapered off with increasing latitude, with lowest values (often below the white noise level) located principally in the stormy areas at higher latitudes over the oceans (fig. 4). The trend was moderately large over the polar cap in summer and fall and was generally substantial in the interior of Asia and other desert areas. There was some tendency for the areas of maximum trend over the continents to shift northward from winter to summer, indicating a possible relationship with normal seasonal changes in the general circulation. Thus it appears that the long-term trend represents slow changes in the strength of the subtropical Highs and continent-ocean monsoonal circulations. This is in agreement with earlier findings of Willett (1961, 1965) and Brier (1947). The latter investigator discussed only the historical series data from 1899 to 1938.

The trend was so widespread that it showed up in the spectrum analysis of the mean data for the whole hemisphere, indicating that there may be an interchange of air between hemispheres in the long term. Brier's (1947) figure 2 shows this quite well and suggests that the lowest overall pressure may have been reached in the 1930s.

Roden (1965), on the other hand, reported no significant trend in his analysis of sea-level pressure data at several stations along the Pacific coast of North America. His results are not necessarily contradictory, however, since figure 4 shows that there was little trend along the west coast of North America, except from California southward during spring and fall. An additional factor that might have led to some differences in results is that the data series analyzed by Roden began in 1873 rather than in 1899. If there is an 80- to 90-yr periodicity in atmospheric parameters, this would not have appeared as trend in Roden's data but could have appeared masked as trend in a shorter sample.

It was feared that some of the large trends observed could have been spuriously introduced if the barometer of some key station in an area of sparse data had been moved or if the method of reduction to sea level had been changed. Such changes do occur from time to time and would be serious particularly at high-altitude or low-latitude stations. In this respect, the large trend in the Mexico area (fig. 4) was especially suspect.

As a check, the standard deviations of winter sea-level pressure were plotted for several grid points that displayed unusually large values of trend. Inspection of the graphs disclosed a smooth and gradual change in pressure throughout the period of record at most of the

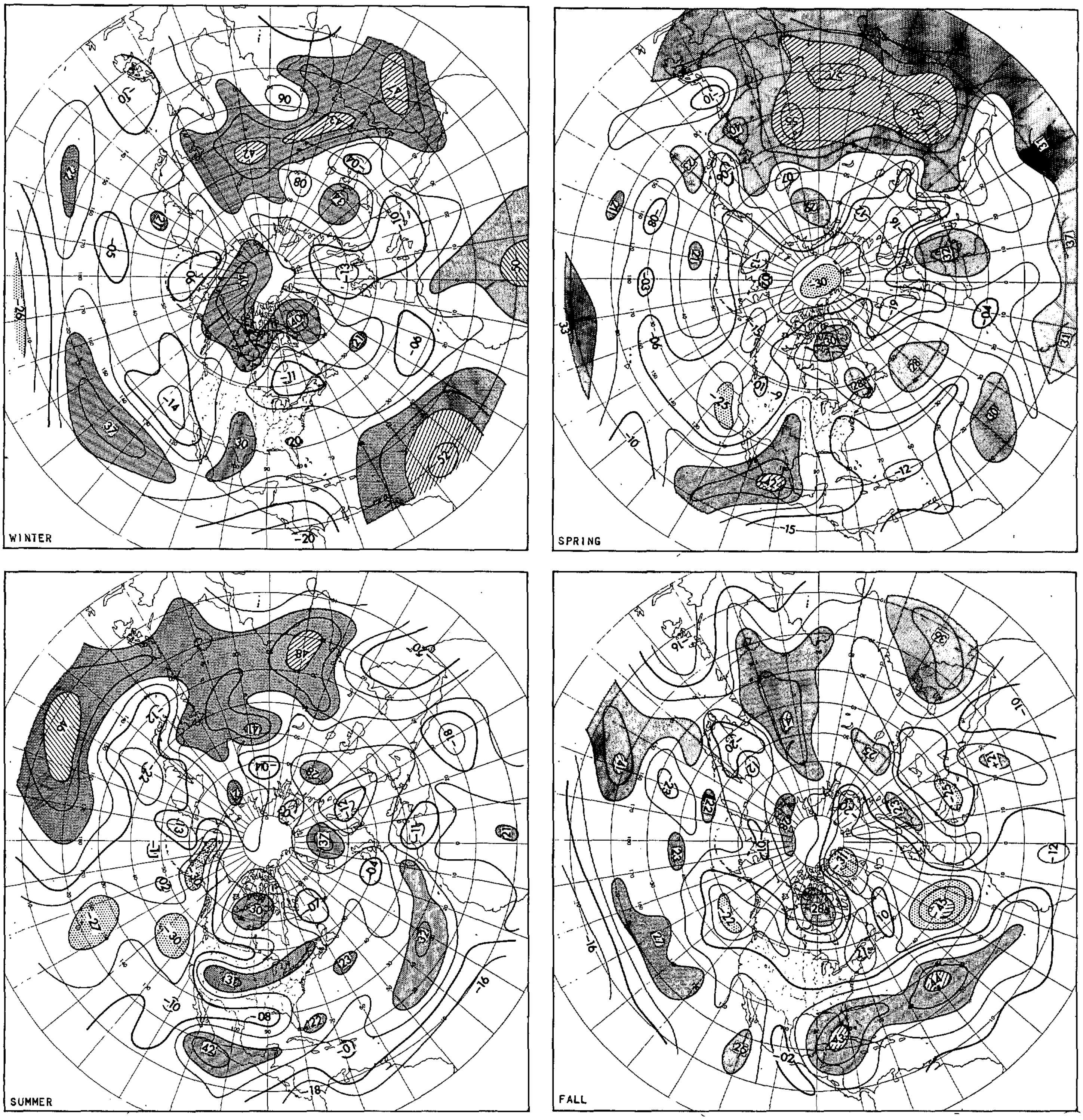

FIGURE 3.—Hemispheric distribution of the ratio $(r_2-r_1^2)/(1-r_1^2)$ for the four seasons. Areas where the ratio is greater than ± 0.2 are shaded, and areas where it exceeds ± 0.4 are hatched. The analysis is at intervals of 0.1, with the zero line heavier. Central values are labeled in hundredths.

points checked. In particular, there was no suggestion of a discontinuity at the grid point near Mexico City. It should be noted, however, that the text accompanying the U.S. Weather Bureau (1952) normal charts mentions that, during much of the original historical series, the thermal trough in the southwestern United States and Mexico had been smoothed out too much in the analyses. This could have introduced a spurious component of trend in that area.

The data series near Davis Strait showed a possible discontinuity around 1938; although in northwest Canada, the record appeared smooth. The Davis Strait discontinuity is probably in part a reflection of the error in the polar area also mentioned in the text with the U.S.

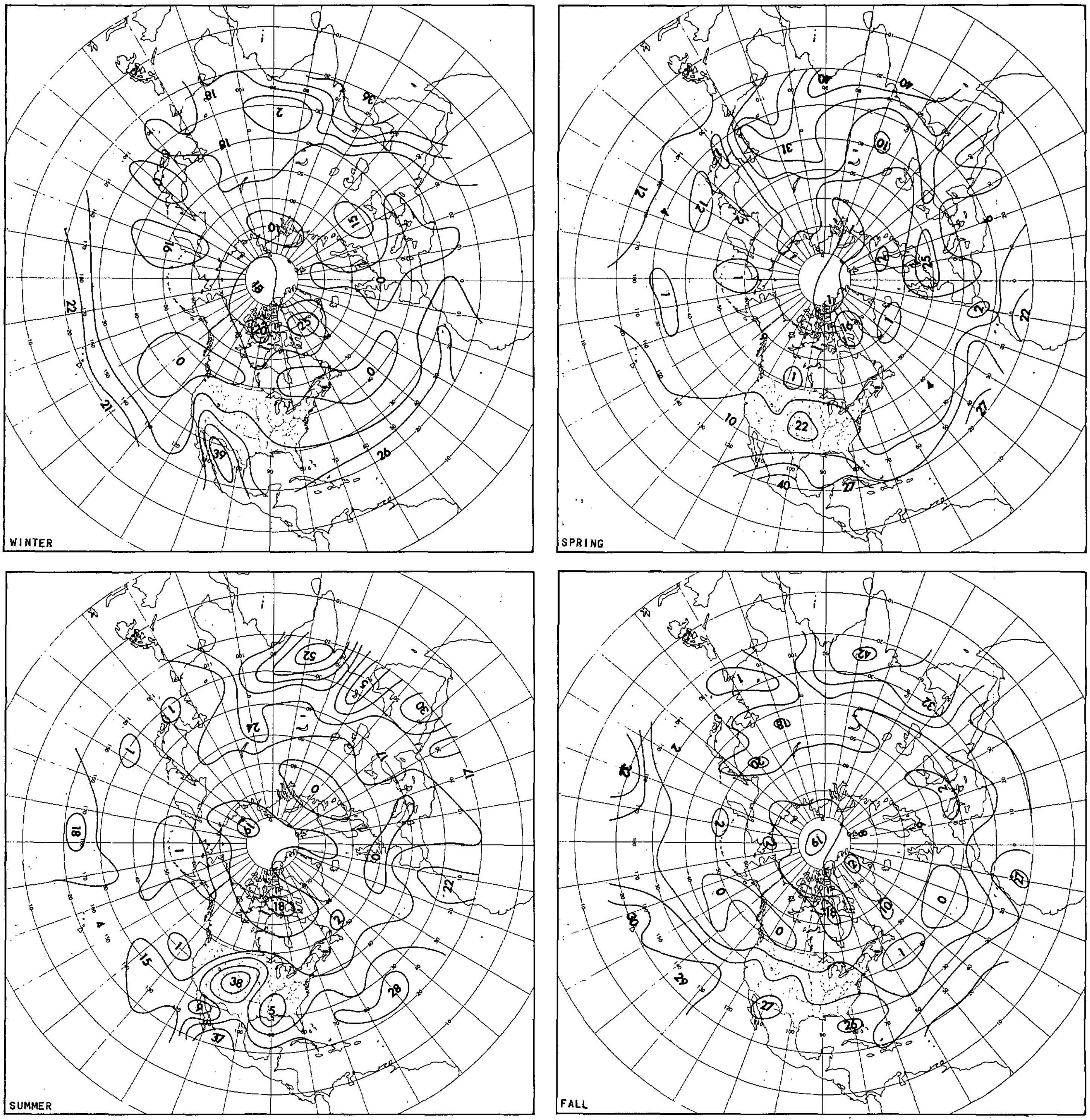

FIGURE 4.—Hemispheric distribution of magnitude of the spectral coefficient C_0 corresponding to trend of the standardized departure of sea-level pressure from normal for the four seasons. The analysis is for every 8 hundredths, beginning at 2 hundredths. (The white noise level in this figure and in figs. 5–9 is a little less than 5 hundredths.)

Weather Bureau (1952) monthly normal chart series. The only other point showing a possible discontinuity was in India; and in that case, the discontinuity may have been more apparent than real, since 12-yr data were missing during and following World War II.

There is some risk that errors due to preconceived ideas of what the pressure should have been during the early part of the record might have introduced spurious trend at some of the low-latitude oceanic areas with poor data coverage. It is impossible to state just how much this error could have been, if any, although the fact that the trend is just about as large over land areas at low latitudes is encouraging. Certainly, the large values of trend observed over the southwestern United States and including the

Rockies and Great Plains could not be due to erroneous extrapolation due to lack of data; although as noted above, a spurious component of trend could have been introduced by excessive smoothing of the thermal trough during the earlier part of the record.

It is noteworthy that nearly all the trends of winter sea-level pressure that were plotted were negative. The only exception was the Davis Strait point. This result was considered at first puzzling, especially in view of the large negative trend disclosed by the analysis of the data from northwest Canada. However, Willett's (1961) figure 5 shows a strong gradient of annual temperature change across northern Canada, with negative values over the central part and positive values over Greenland and Davis Strait. Since abnormally high temperatures in northeast Canada are associated with blocking Highs and rising pressure both at the surface and aloft near and to the east of the area, the apparently anomalous increase in winter sea-level pressure near Davis Strait is not inconsistent with other observations and may not be entirely attributable to the suspected analysis extrapolation errors referred to previously. The winter season would have the dominating influence on annual nonstandardized temperatures, especially at high-latitude or continental locations.

It is also possible that a change in observation time between hours when the diurnal sea-level pressure change is large could have introduced spurious trend into the sea-level pressure record. Beginning June 1, 1957, the times of the principal 6-hr synoptic surface observations were moved back a half hour, so that what used to be the 1230 GMT observation is now taken at 1200 GMT. This is a time of fairly strong diurnal rise in pressure over much of the United States, as seen from the U.S. Weather Bureau (1943*b*) compilation of pressure tendencies and hourly station pressures. The change to an earlier observation time would give slightly lower readings in the data from recent years over at least the eastern portions of North America, leading to a small amount of spurious negative trend in the 1899–1964 data series in that area. Since the standard deviations of seasonal mean sea level pressure are on the order of 1 or 2 mb over eastern North America and the half-hour diurnal changes around 1200 GMT for the most part not over a fifth of that, it is unlikely that appreciable spurious trend could have been introduced into the data from the half-hour change in observation time commencing June 1, 1957.

On a hemisphere-wide basis, the diurnal (or more specifically the semidiurnal) tendency increases as one approaches the Equator, thus perhaps again raising a slight doubt as to the origin of the trends near 20°N, particularly since the seasonal standard deviations of sea-level pressure are smaller at low latitudes. If the change in observation time were introducing spurious trend, there would be not only some suggestion of a discontinuity in the data series around 1957 but also the trends woul l be opposed at different longitudes due to the geographical location of the diurnal and semidiurnal pressure waves. This was clearly not the case as all the lo.v-latitude points displayed negative trend. Thus we may conclude that the trend revealed by the spectrum analysis of seasonal sea-level pressure standard deviation ratios over the Northern Hemisphere discloses a real long-term decrease in atmospheric pressure, primarily at low latitudes, for the period of data analyzed covering approximately the first two-thirds of the 20th century.

Turning now to the other long periods resolved by the spectrum analysis, we find that the largest values of power in the spectral band centered at 21 yr are found generally over Asia at lower middle latitudes (fig. 5). The peak values, ranging from 20 in fall to 31 in summer, are four to six times the white noise level, and the areas of spectral power greater than twice the white noise level are of sufficient lateral extent to represent apparently something of meteorological significance. Other areas of substantially high values of spectral power were located over North Africa or Arabia and over Western North America. The areas of spectral power centered at a period of 21 yr thus appear to often coincide with semiarid and desert regions of the earth's surface. Of particular interest is the strong Asian maximum during winter, centered just south of the mean winter position of the Siberian High.

These findings may be connected with the approximately 20-yr cycle in precipitation found by Willett (1965) over parts of the western and central United States. He found that the U.S. precipitation cycle appeared to be defined best over arid and semiarid areas.

The distribution of spectral power for the band centered at 10.5 yr is not displayed in map form, as it did not have such strong maxima or apparently coherent patterns as the 21-yr period. It is of interest to note, however, that many of the points displaying the strongest spectral power at 10.5 yr from the winter sea-level data were located at high latitudes. Sea-level pressures in these same areas had been shown previously by Craig (1951) and Willett (1961) to be responsive to variable solar activity on both a short-term and long-term basis, with the most noticeable effects in the colder part of the year.

VARIATIONS WITH INTERMEDIATE PERIODS

Periods of intermediate length that contained considerable spectral power over most of the Pacific Ocean, particularly during summer and winter, were 5.3 and 6.0 yr. The peaks in the individual spectra were not particularly sharp in this range, but the power was at least twice the white noise level over a broad expanse of the Pacific at both these periods. The hemispheric distribution of the spectral power centered at 6.0 yr is shown in figure 6. It can be seen that the power was greatest over the Pacific during summer and winter and over portions of the eastern North Atlantic during spring and fall. Relatively high spectral power was in evidence over North America during the fall and winter also, particularly near or just south of the normal tracks of the Alberta Lows, which are most active in those seasons (Klein 1957).

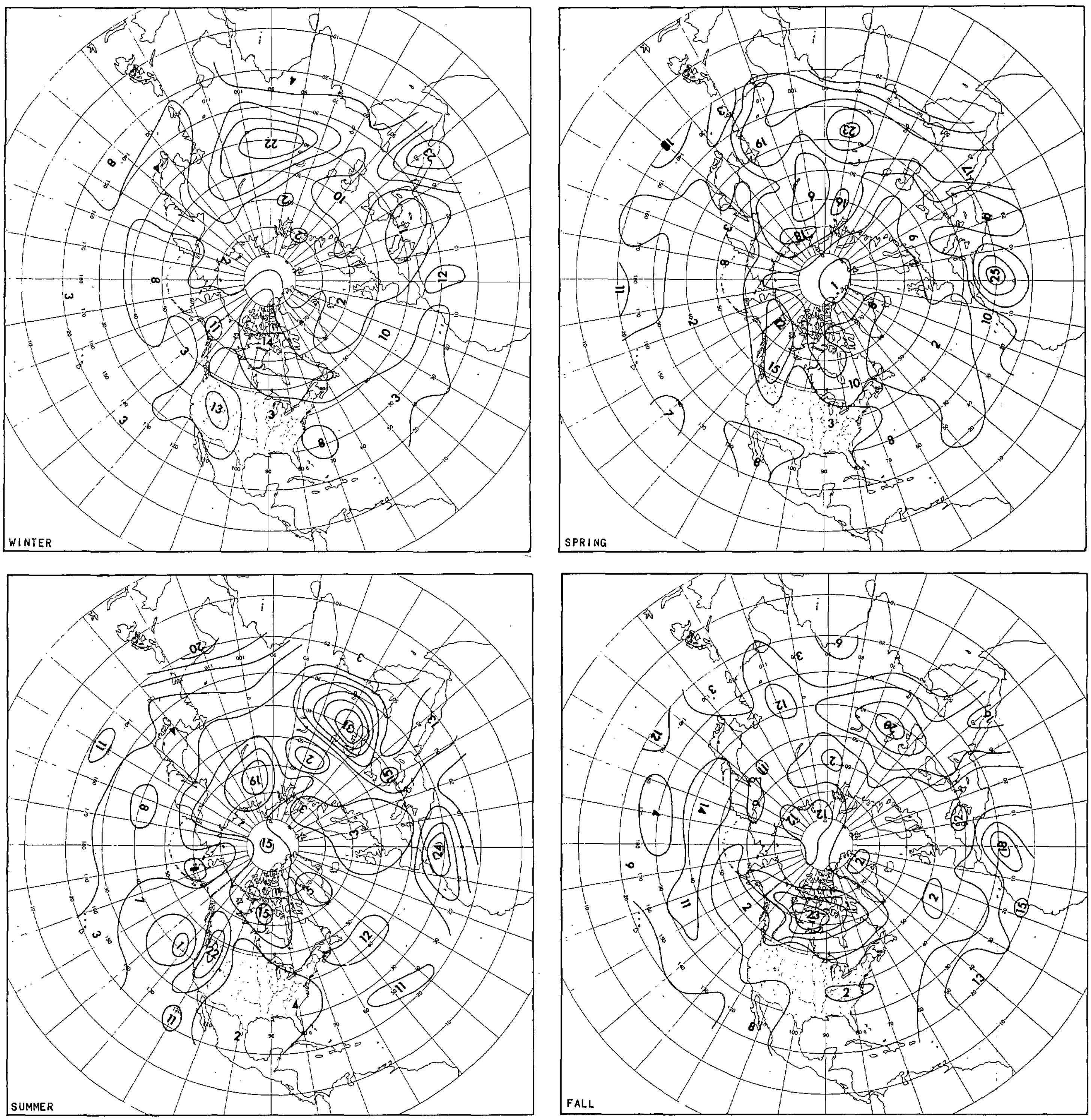

FIGURE 5.—Hemispheric distribution of magnitude of the spectral coefficients C_2 corresponding to a period band centered near 21 yr in the standard departure of sea-level pressure from normal for the four seasons. The analysis is for every 4 hundredths, beginning at 2 hundredths.

The fact that the areas of relatively large spectral power near 6 yr during winter and summer appear to cover much of the middle- and high-latitude portions of the Pacific Ocean raises the interesting possibility that a large part of the Pacific Ocean may have been acting as a feedback system with the overlying atmosphere, with a tendency for resonance at a period near 6 yr. Namias (1969) has found that a quasi-steady regime with large-scale anomalies of both sea-surface temperature and atmospheric pressure persisted for several years in the Pacific with minor fluctuations after a rather sudden onset in the fall of 1961. There is some suggestion of a

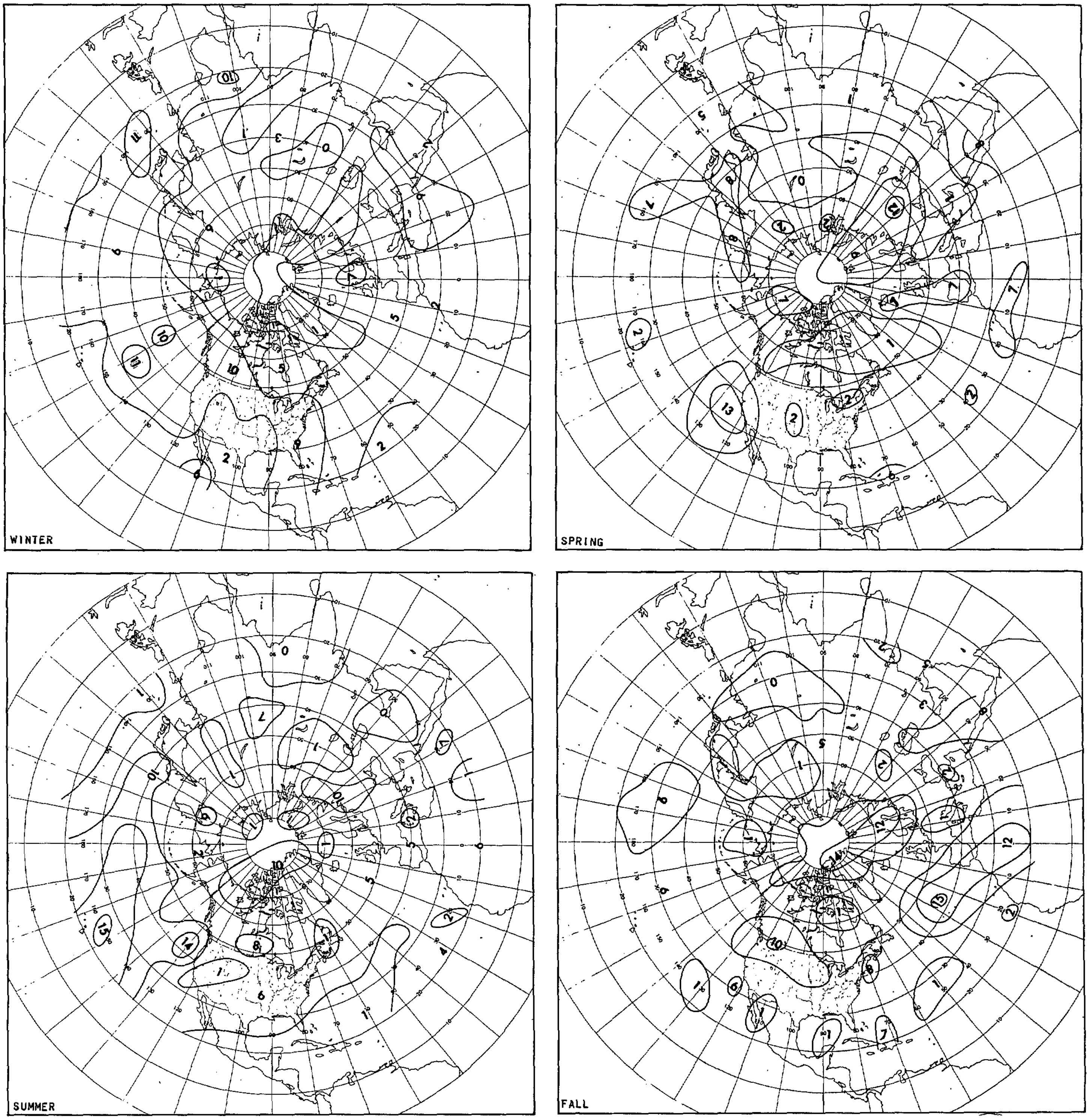

FIGURE 6.—Hemispheric distribution of magnitude of the spectral coefficient C_7 corresponding to a period near 6 yr in the standardized departure of sea-level pressure from normal for the four seasons. The analysis is for every 4 hundredths, beginning at 2 hundredths.

5- to 7-yr period in the sea-surface temperatures analyzed in figure 15 of Namias' paper. Since the frequency of Alberta Lows is related to the longitudinal position of the mean Gulf of Alaska-Aleutian Low (DeCoster 1945), the high spectral power near the Western United States-Canada border may be related to the primary variations over the Pacific.

Roden (1964), in a study of monthly mean sea surface temperatures along the Pacific coast of North America, found that anomalies of like sign rarely lasted more than 2 yr. On the other hand, Acara (1962) discovered evidence for a 4- to 5-yr period in surface water temperature measured farther out in the ocean, with an opposition in phase between the eastern and western Pacific.

Such a phase opposition might be the surface manifestation of a periodic fluctuation in the strength and/or position of the mean 700-mb trough often found in the eastern or central Pacific (Stark 1965) during winter. In summer, the water temperatures would be influenced more likely by variations in the large anticyclone located generally in the east-central Pacific at mid-latitudes. As pointed out by Namias (1969), Bjerknes (1969), and many other authors, anomalous sea-surface temperatures are generated by change in the advection of surface water, upwelling or downwelling, extraction of sensible and latent heat, and insolation, all related to variations in the long-term mean atmospheric circulation both at the surface and aloft. When strong and highly persistent, these influences extend frequently to deeper layers of the ocean, so that the water temperature anomalies persist from year to year even though brief interrupting atmospheric regimes may temporarily modify shallow surface layers. Recurrent and persistent ocean temperature anomalies may act in turn as "forcing functions" to predispose the atmospheric circulation to depart from normal in the same general sense for a number of successive years.

PERIODS IN THE QUASI-BIENNIAL RANGE

There were few areas that displayed substantial spectral power peaks in the range of periods resolved between 2.5 and 3.0 yr. The hemispheric distribution of spectral power in the band centered at just under 2.5 yr (29.7 mo) is shown in figure 7. Two rather extensive areas with central maxima about three times the white noise level were found during the winter season, one in the Gulf of Alaska and the other over southern Europe and the Mediterranean. Both of these areas are characterized by frequent cyclonic activity during the cold part of the year. Smaller maxima over the central Atlantic and west of Spitzbergen may be related to the primary centers as "teleconnections" (Namias 1953). There is a strong tendency for winter storms in the Atlantic to either move on a northeasterly track toward Iceland and the Norwegian Sea or drop southeastward into the Mediterranean, depending on the latitude of the main band of westerlies and the presence or absence of blocking over northern Europe.

The patterns of spectral power near 2.5 yr are weaker during the other three seasons, especially spring and fall when peak values are mostly less than twice the white noise level. During spring, maximum values are found to the south of the mean position of the Icelandic Low, in the Mediterranean area, near Japan and Manchuria, and along the British Columbia coast.

During summer, maxima are observed over the Canadian Prairies, near the British Isles, and north of Scandinavia near Novaya Zemlya. These are all areas of occasional but not regular cyclonic activity in summer. An extensive area of relatively high power also appears in the western Pacific at 20°–30°N, possibly in connection with the tropical cyclonic activity that is commonplace in that area during summer and early fall. No corresponding area of relatively high spectral power was found in low latitudes of the Atlantic, perhaps because the tropical storm season gets underway later in the Atlantic than in the Pacific.

In the fall, there is some tendency for the maximum 2.5-yr spectral power to be observed at relatively high latitudes in accordance with the high-latitude storm paths more common at that time of year. The fall maximum in the Aleutian area is displaced westward from the winter position, in accordance with the mean position of the northern part of the central Pacific trough. In all four seasons, areas of relatively high spectral power at 2.5 yr appeared to be located in or near regions characterized by cyclonic activity, particularly at mid-high latitudes. This is in basic agreement with recent findings by Angell et al. (1969) that some of the dominant periodicities in the position of the Pacific Low were near 30 mo.

Maps of spectral power at 28.0 mo are not shown in this article even though there was about as much overall power at 28.0 mo as at 26.5 mo. It was felt that the distinction of details between two or three immediately adjacent spectral bands might not be very significant. For example, the winter data displayed a maximum at 28.0 mo over much of the Pacific along a latitude band near 40°N located between the positions of maxima at 29.7 mo centered near 50°N and at 26.5 mo oriented along 30°N. It is not known whether this represents a true spectral maximum at 28.0 mo in that area or a "blurring" of the maxima at adjacent periods in areas to the north or south. The results of Angell et al. (1969) suggest that, at least for the Atlantic, the 28-mo period is a real entity.

Figure 8 shows the distribution of spectral power density at a period of 2.2 yr or just about 26.5 mo, the generally accepted average period of what has come to be known as the quasi-biennial oscillation (Reed 1965). During winter, the hemispheric 2.2-yr spectral power pattern is quite different from what it was for a 2.5-yr period. In contrast to the affinity of maxima at 2.5 yr for areas of cyclonic activity, the 2.2-yr power seems to be greatest in or near areas of anticyclonic activity. Peak values, mostly more than twice the white noise level, are found over northern Asia, in a strip extending southeastward from northern Alaska to the central United States very close to the mean winter path of arctic Highs (Klein 1957), and to the north of the oceanic ridges in the Atlantic and Pacific. There is also a maximum in the western Europe and Mediterranean area.

The rather extensive area of high spectral power at 2.2 yr near latitude 30°N in the Pacific may be related to findings of Krueger and Gray (1969) and Bjerknes (1969) of quasi-biennial variations in equatorial circulation and rainfall, as well as other parameters, over the Pacific. Krueger and Gray point out that the subtropical High

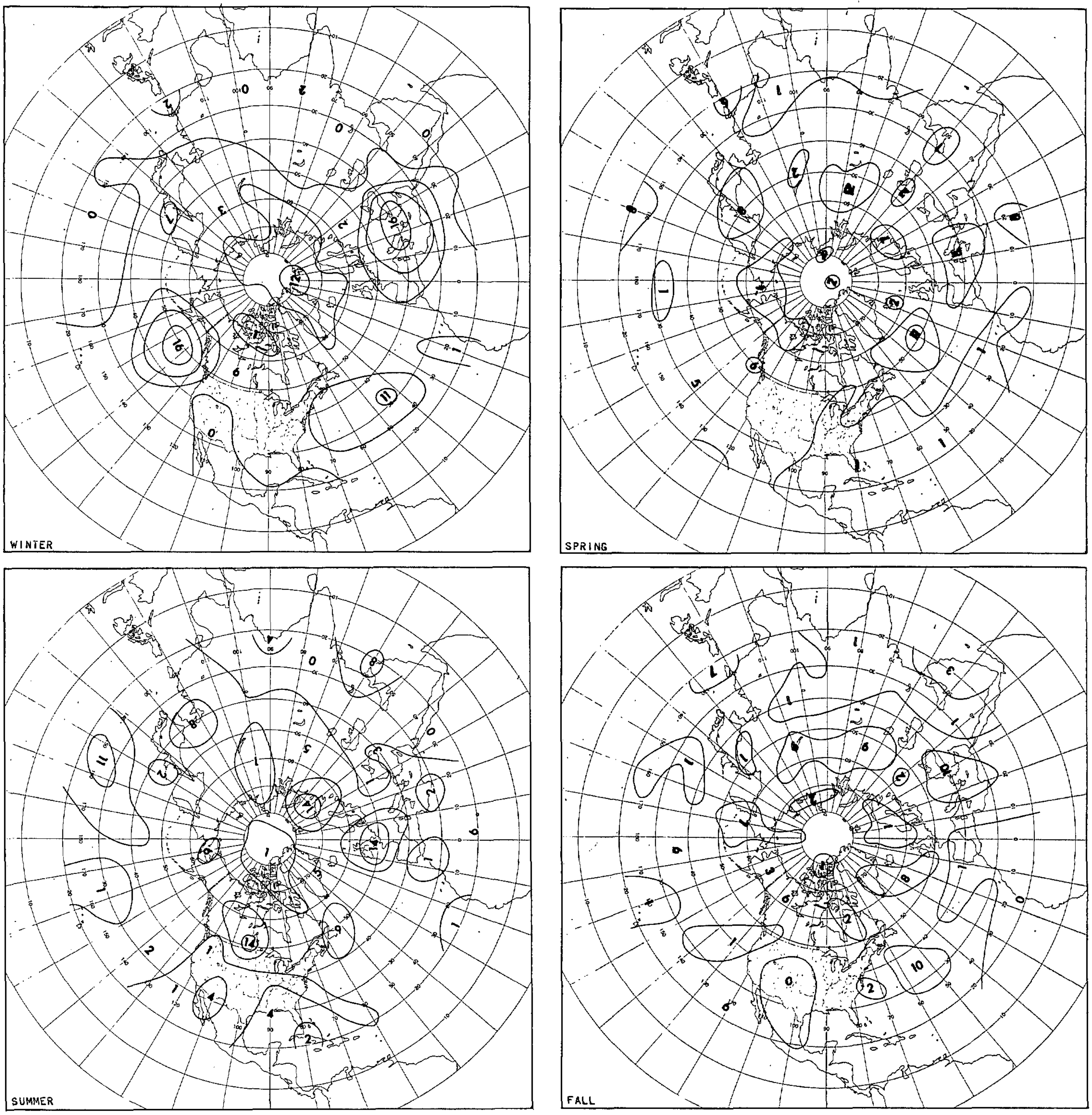

FIGURE 7.—Hemispheric distribution of magnitude of the spectral coefficient C_{17} corresponding to a period of approximately 2.5 yr or 29.7 mo in the standardized departure of sea-level pressure from normal for the four seasons. Analysis is for every 4 hundredths, beginning at 2 hundredths.

belt and even mid-latitude circulations would be expected to vary along with the equatorial circulations due to interchange of momentum and energy between latitudes.

Since temperature is related to the pressure gradient and type of prevailing air masses over most mid-latitude regions, it is of interest to note that both Clough (1924*a*, 1924*b*) and Landsberg et al. (1963) have found evidence of the QBO in temperature and pressure records from Europe, southeastern Canada, and the northeastern United States. Clough, by the way, may be one of the "discoverers" of the QBO, although he did not refer to it by its modern name.

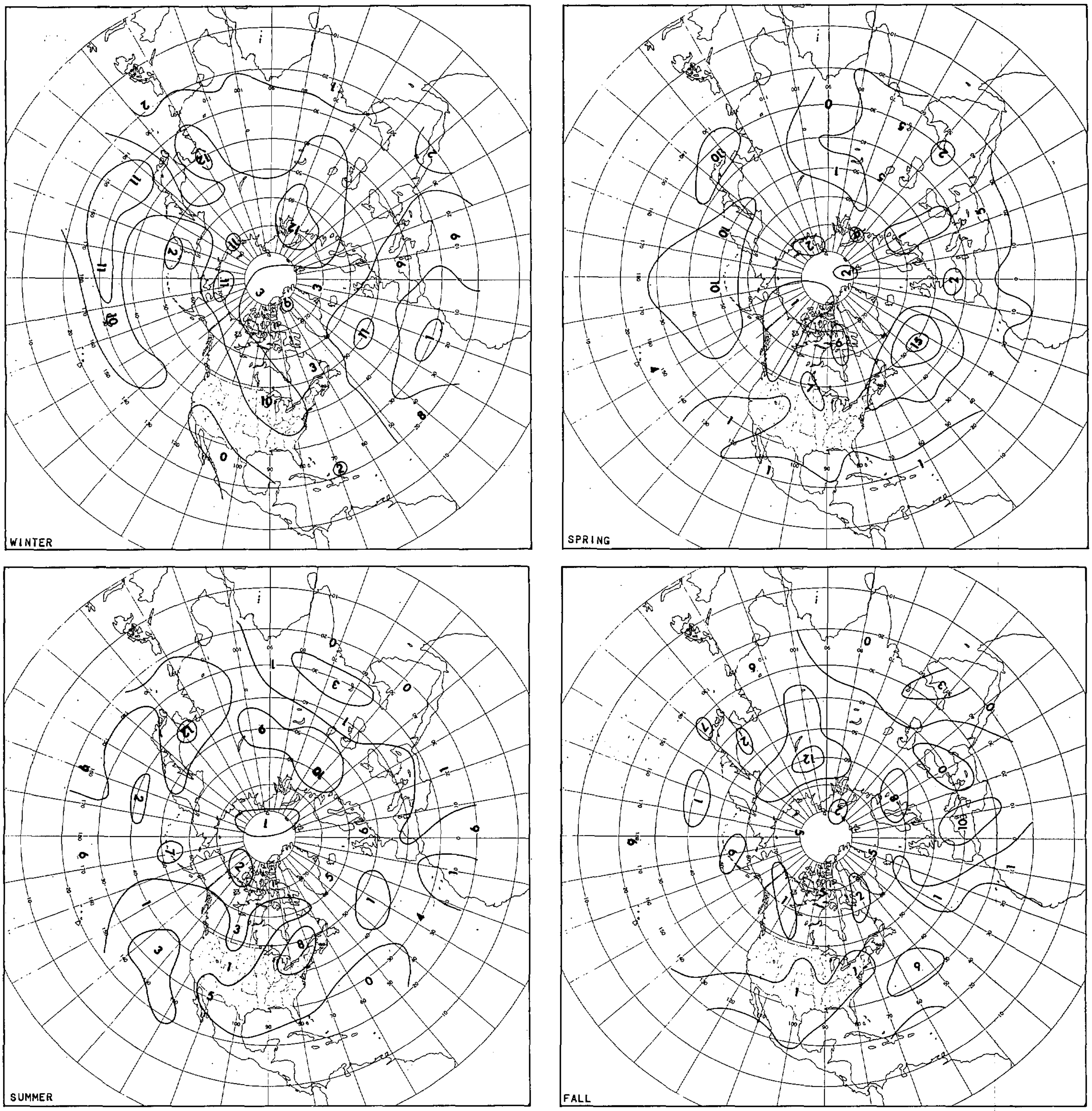

FIGURE 8.—Hemispheric distribution of magnitude of spectral coefficient C_{19} corresponding to a period of approximately 2.2 yr or 26.5 mo in the standardized departure of sea-level pressure from normal for the four seasons. Analysis is for every 4 hundredths, beginning at 2 hundreths.

The relationship between relatively high spectral power at 26.5 mo and areas of anticyclonic activity does not hold up as well in the other seasons, except for centers near the Siberian and Bermuda Highs in the fall.

The spring 2.2-yr spectral maxima appear close to the areas of maximum power at 2.5 yr for the same season (compare figs. 7 and 8). During summer, areas of relatively large spectral power appear over north-central Asia, the Pacific coast of Asia, the southwest Pacific, and the St. Lawrence area of eastern North America. During fall, in addition to the previously mentioned maxima found north of Lake Baikal and near Bermuda, considerable

2.2-yr spectral power was located over Scandanavia and the Mediterranean.

The rather extensive areas of relatively high power at both 2.2 and 2.5 yr that were found over the oceans are probably manifestations of the phenomenon recently discovered by Angell et al. (1969). Using monthly data with annual trend removed, they discovered quasi-biennial variations in the position as well as the strength of the subtropical Highs and subpolar Lows with the period averaging 26–27 mo at low latitudes but 28–30 mo at higher latitudes in the vicinity of the subpolar Lows. The relative phases of the oscillations were such as to create a rather strong quasi-biennial variation in the strength of the North Atlantic mid-latitude westerlies. Other authors (Brier 1968 and Murray and Moffitt 1969) also found rather good evidence of a biennial oscillation in zonal wind at mid-latitudes during certain months of the year, while the QBO was weakly indicated at other times.

Angell et al. (1969) have reported evidence for a quasi-biennial oscillation in the number of typhoons in the western Pacific, related to the variation in the position and strength of the subtropical High. The distribution of spectral power for both 2.2 yr (fig. 8) and 2.5 yr showed maxima in the southwestern Pacific south of the summer axis of the subtropical High belt.

The seasonal hemispheric spectral power distributions for the band centered at 2.0 yr are not shown. In general, there was less power at exactly 2 yr than at any other period in the entire spectrum. This finding served to emphasize that the spectral power peaks in the short-period end of the spectrum occurred mainly at periods somewhat longer than 2 yr. This is in agreement with the results of nearly all other investigations of the QBO, which show that the average period, although often variable in both length and amplitude, was somewhat greater than 2 and less than 2½ yr (Reed 1965).

It was impossible to make a satisfactory (both rigorous and simple) statistical test of the significance of the quasi-biennial spectral peaks. As Nordö (1966) has shown, it is difficult to estimate the significance of peaks at the short period end of the spectrum for a geophysical time series characterized by a large amount of trend (red noise) and a considerable departure from a first-order Markov process. This was obviously the case with much of the data analyzed in this paper.

The relative sharpness of the spectral peaks in the quasi-biennial range was estimated by comparing the power at 26.5 and 28.0 mo with the power in neighboring spectral bands. In figure 9, the hemispheric distribution of the ratio $3(C_{18}+C_{19})/(C_{16}+C_{17}+C_{18}+C_{19}+C_{20}+C_{21})$ is shown for each season. If the power distribution were essentially flat or were merely the high-frequency end of a smooth red noise spectrum, the values of this number would be close to 1.0—the sharper the spectral peak in the quasi-biennial range, the more the value of this ratio exceeds 1.0. A peak in the spectrum near either 2 or 2½ yr would result in values of the ratio being less than unity.

The most extensive areas showing spectral power concentrated in the true quasi-biennial range are observed with the winter season data. Especially noteworthy are the areas in the southwest and south-central Pacific, along the arctic coast of Alaska and northwestern Canada, and in the central Atlantic, where the value of the "sharpness ratio" exceeded 2.0. The Pacific area may be associated with the quasi-biennial variations of various parameters reported by Krueger and Gray (1969).

The Atlantic area is in the vicinity of the maximum gradient of the difference between odd and even winters' sea-level pressures shown by Murray and Moffitt (1969). It should be noted, however, that they used a technique emphasizing a period of exactly 2.0 yr, rather than the QBO of 2.2 to 2.3 yr. Also, Murray and Moffitt pointed out that there was actually a tendency for January to be out of phase with December and February within a given whole winter season, so their results are not directly comparable. The current investigation did disclose a band of moderately high 2.0-yr spectral power extending across the mid-Atlantic during spring and summer (not shown). These were about the strongest of any power concentrations at exactly 2.0 yr anywhere in the Northern Hemisphere.

The area of sharp quasi-biennial spectral power over northwestern Canada would be closely related to the frequency and intensity of arctic Highs entering North America or forming in that region. The coldness of winters over the United States, however, would of course also be related to the frequency and severity of arctic outbreaks actually entering the country, which is determined by other parameters in addition to the frequency of occurrence of cold Highs in northwestern Canada. Nevertheless, Clough (1924*a*, 1924*b*) and Landsberg et al. (1963) did report evidence of quasi-biennial fluctuations in temperature as well as pressure over northeastern United States and southeastern Canada.

The only areas showing a fairly sharp quasi-biennial spectral peak during spring were Manchuria and the central Atlantic. The area in the Atlantic is probably associated with the oscillation of the Bermuda High described by Angell et al. (1969).

During summer, the sharpest spectral peaks in the quasi-biennial range were found at low latitudes of the central Atlantic and western Pacific. Angell et al. (1969) found evidence of a biennial variation in typhoons associated with the oscillation of the Pacific High, but somewhat weaker indications of a QBO in Atlantic hurricane frequency. This may have been due to the fact that frequently about half the "Atlantic" hurricanes originate in the Caribbean and Gulf of Mexico, areas displaying sharpness ratios of less than 1.0. Only part of the China Sea had ratios less than 1.0 in the Pacific region, and a relatively smaller percentage of Pacific typhoons originate in or traverse that area.

Fewer and smaller areas had sharp quasi-biennial spectral peaks in fall than in any other season. Areas with the sharpest coefficients (not over 2.0 anywhere) were the south-central Pacific and North Africa and possibly south of Mexico in an area characterized by recurrent tropical cyclogenesis. This is consistent with the results of Angell and Korshover (1968) who detected

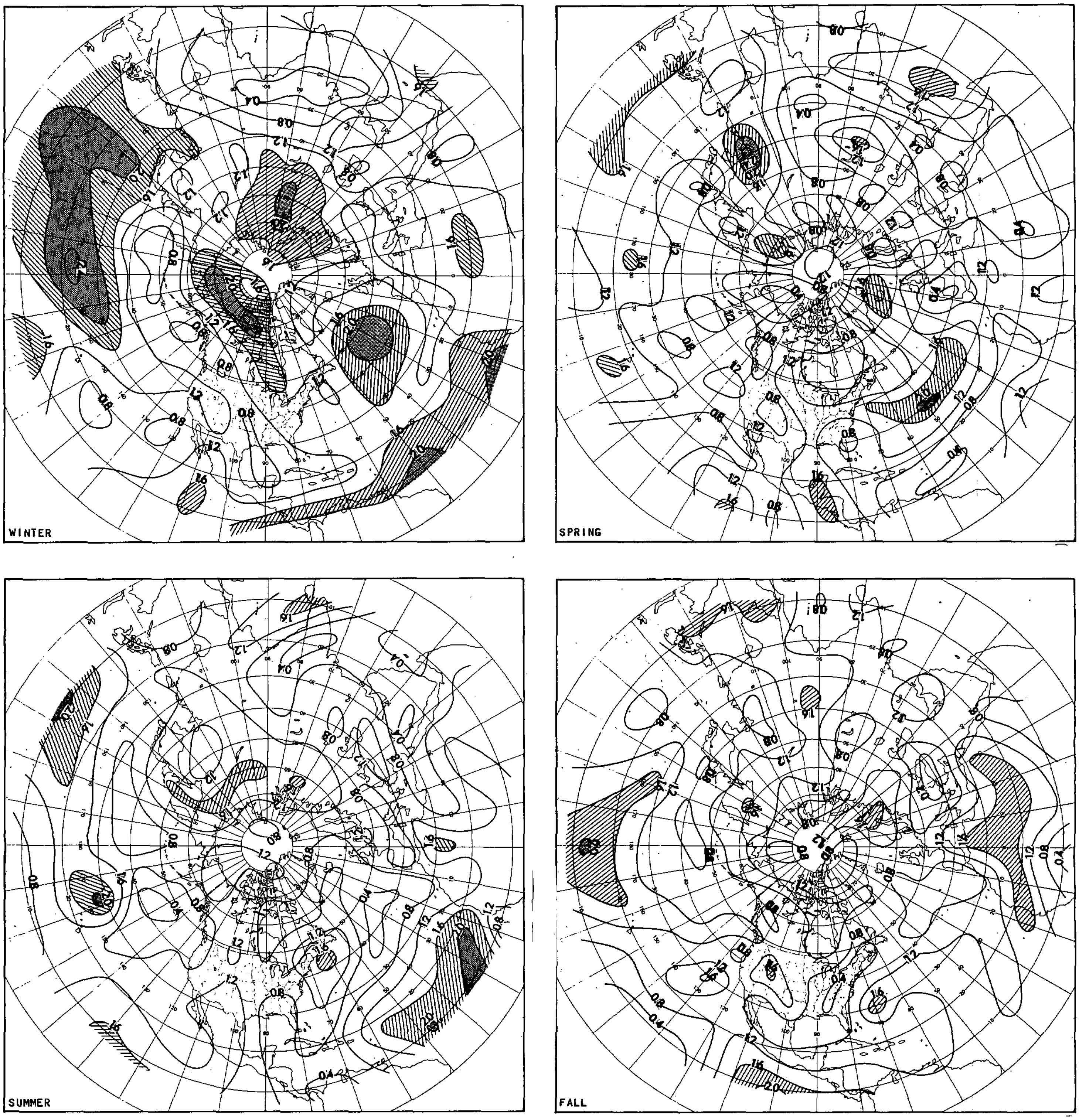

FIGURE 9.—Hemispheric distribution of the sharpness of the quasi-biennial peak in the time spectra of the standardized departure of sea-level pressure from normal for the four seasons. The sharpness of the quasi-biennial peak was measured by the ratio $3(C_{18}+C_{19})/(C_{16}+C_{17}+C_{18}+C_{19}+C_{20}+C_{21})$ where the Cs are the spectral coefficients corresponding to periods in the range of 24.0 to 31.5 mo. The analysis is at intervals of 4 tenths. Areas with ratios greater than 1.6 are hatched, and areas with ratios greater than 2.0 are shaded.

the QBO in various tropospheric parameters during the months January through May but found practically no evidence of it from July through November. Brier (1968) found the strongest evidence of the QBO in mid-latitude westerlies in winter-month data, although other months scattered throughout the year had fairly high power in his QBO range (from 2.00 to 2.41 yr).

The fact that different analysis techniques by several authors, all using basically the same original data source, show the QBO to be mainifested most strongly during winter would thus indicate a more than coincidental relationship between the QBO and the cold season. In particular, the evidence of greatest QBO strength in standardized data during winter indicates that it may tend

TABLE 1.—*Total number of points with spectral peaks near each period in the high-frequency end of the spectrum for the four seasons*

Coefficient number Period in months		16 31.5	17 29.7	18 28.0	19 26.5	20 25.2	21 24.0	Total counts
Total number of peaks:	Winter	7	31	62	81	21	18	220
	Spring	30	34	47	39	15	20	185
	Summer	31	28	38	32	29	22	180
	Fall	23	22	28	36	17	17	143
	Grand totals	91	115	175	188	82	77	728

to "lock in" on the coldest part of the year. A relationship of this type is not surprising in the light of a remark by Miller et al. (1967) that the QBO could be influenced by continent-ocean thermal contrasts.

Areas where the quasi-biennial sharpness ratio was less than 1.0 were characterized by peaks in the spectrum either near 2.0 or 2.5 yr. In particular, the rather extensive areas in the North Pacific where the sharpness ratio was near or less than 0.8 are where there was a rather broad spectral peak in the vicinity of 2.5 yr. Compare figures 7, 8, and 9 and note the result of Angell et al. (1969) showing moderate peaks in the time spectra near 2.5 yr for the position of the Pacific Low. Some of the low-latitude points displaying sharpness ratios of less than 1.0 had pronounced spectral peaks at exactly 2.0 yr.

A measure of the world-wide reality of the QBO in surface-pressure data may also be obtained simply by adding the number of points in the Northern Hemisphere that had spectral peaks at each of the periods near to and including the quasi-biennial range. This was done for each of the four seasons, and the results are shown in table 1. For purposes of counting, when a spectrum did not have one clear peak, if two adjacent periods had equal power and were highest in the range, each was assigned a count of ½. If three adjacent periods had the same and highest power, the central one was assigned a count of 1. If four or more adjacent spectral coefficients made a plateau without a defined peak, none of them were counted. If there were two distinct peaks within the last six coefficients, only the higher of the two was counted. (This actually happened quite rarely.) In table 1, the sum of the counts for each season is also given—the flatter the high-frequency end of the spectrum, the lower the total count of points having spectral peaks.

Clearly, the quasi-biennial peaks were most strongly defined during the winter season, and there were fewer "flat" spectra at high frequencies then also. The QBO was apparently weakest, at least in areal extent, during summer and fall, in general agreement with the results of Angell and Korshover (1968). The spectra themselves were flattest at the high-frequency end during the fall, and most clearly peaked (at 26.5 mo) during winter. An additional interesting fact disclosed in table 1 is that a slightly greater number of peaks in the spectra are shifted to 28.0 mo rather than 26.5 mo during spring and summer. Overall, there is a clear preponderance of points having spectral peaks near either 26.5 or 28.0 mo rather than adjacent periods in the range of 24.0 to 31.5 mo. Angell et al. (1969) noted that, at mid-latitudes, the apparent preferred period of the QBO was about 1 mo longer than at low latitudes, and it can be seen from table 1 that overall there were nearly as many points with peaks at 28.0 mo as at 26.5 mo.

4. SUMMARY AND CONCLUSIONS

Spectrum analysis of 66 yr of sea-level pressure standard deviation ratios over the Northern Hemisphere revealed that the predominant characteristic of the data at most points was trend. Closer examination of the data series at several points that displayed unusually large trend did not disclose evidence of discontinuities that would have introduced spurious trend. The change in world-wide synoptic observation time by half an hour in 1957 did not appear to be sufficient to introduce spurious trend due to the diurnal pressure tendency, and no evidence of an error from that source was found. Most of the points with large trend, both continental and maritime, had a decreasing sea-level pressure through the period of record covering approximately the first two-thirds of the 20th century. This trend in sea-level pressure is probably related to temperature trends discussed by other investigators.

The points showing the largest values of trend were at low latitudes, either near the subtropical high-pressure belt or in areas dominated by monsoonal circulations. As might be expected, these same locations were generally characterized by large values of 1- and 2-year-lag autocorrelations, and the associated spectra had most of their power in trend or low frequencies. This type of power spectrum, common for geophysical data series, is said to contain a large amount of red noise. Because of this characteristic and the fact that the data series also departed considerably from a first-order Markov process at many points, it was difficult to make reliable estimates of the significance of peaks at the high-frequency end of the spectrum.

Nevertheless, several apparently real quasi-periodicities were found that appeared to be related to specific geographical or climatological features. Strong spectral power in the band centered at 21 yr was in evidence over desert and semiarid areas, particularly over central Asia where the spectral power was four to six times the white noise level, although not so far above the red noise level. It was felt this pattern had a connection with monsoonal climatic regimes and possibly was related to a rainfall periodicity of around 20 yr found in some of the drier sections of the United States.

An extensive area of the central Pacific Ocean was characterized by rather high spectral power of about twice the white noise level in the range of 5 to 6 yr. The spectral power was strongest in this area during summer and winter. Due to the proximity of this area to the belt of fast westerlies between the Pacific subtropical High belt and the Aleutian Low and in the light of recent studies on Pacific air-sea interactions, it appeared possible that the 5- to 6-yr quasi-periodicity in sea-level pressure over the Pacific could be related to some sort of long-period atmosphere-ocean feedback.

The quasi-biennial oscillation was evident in the sea-level data for all seasons, though most extensively and strongly during winter. Whereas the spectral power in the band centered at 2.5 yr tended to be associated with areas of prevailing cyclonic activity, maxima of power centered in the QBO range of about 2.2 yr were frequently located in or near regions of predominantly anticyclonic circulation. The Pacific subtropical High belt generally had a spectral peak in the QBO range during all seasons, and the Bermuda High did during the fall. The area of the Siberian High showed evidence of the QBO during fall and winter, and the area traversed by North American polar outbreaks had a maximum of spectral power at 2.2 yr during winter.

The limited size of the sample as compared to the resolution obtained from the spectrum analysis, together with the strong red noise characteristics of many points, made it difficult to perform any reliable statistical tests of significance for any of the spectral peaks. It was possible, however, to obtain at least a semiquantitative idea of the relative strength of the QBO by computing the ratio of the spectral power at 2.2 and 2.3 yr to the total power in all periods in the range from 2.0 to 2.6 yr.

The most sharply defined QBO was found at subtropical latitudes during the winter season; and in general, the areas where the spectral power was fairly high at 2.2 yr were also areas where the QBO was well defined relative to the immediate neighboring periods. The strongest evidence of the QBO has been found by other investigators to be in winter; and since even standardized data used in this study showed the QBO to be strongest and most widespread in winter, the close association of the QBO with the winter season may be considered to be well established. The cause for this has not yet been conclusively demonstrated, although it is probably not surprising that if dynamically induced, the QBO would tend to "lock on" to the season with the most vigorous and at times changeable atmospheric circulation.

It is also of interest to note that the maximum QBO effects in the standardized sea-level pressure did not appear at the lowest latitudes analyzed but for the most part between 20° and 30°N. Evidences of the QBO found in the stratospheric winds and temperatures were generally greatest within 10° of the Equator and often were difficult to detect north of 30° latitude (Reed 1965). Since spectrum analysis by itself does not reveal phase relationships, it was not determined whether the QBO in sea-level pressure noted in this study was uniquely related to the well-established QBO in low-latitude stratospheric parameters.

The extensive nature of the QBO in seasonal standardized sea-level pressure data for the Northern Hemisphere was further revealed by simply adding the number of points having a peak in the spectrum at each of six periods between 24.0 and 31.5 mo. The maximum count was at either 26.5 or 28.0 mo during the four seasons. At a period of 26.5 mo, more than twice as many points had a spectral peak during winter than for any other season. The distribution of spectral peaks among the periods between 24.0 and 31.5 mo was more even during summer and fall, and fewer well-defined peaks were found anywhere in the high-frequency end of the spectrum during fall than in any other season. These results were also in agreement with findings by other investigators that the QBO was best defined during winter and spring in parameters measured outside equatorial or very low latitude regions.

The reality of the quasi-biennial oscillation as manifested in seasonal standardized sea-level pressure data over the Northern Hemisphere thus appears to be rather well established, particularly during the winter season. Although not done for this paper, it would be possible to compute a red noise spectrum for the data series at each of the grid points and compare the peaks in the spectra with that instead of white noise. Even this procedure would not be rigorously conclusive as to a significance test for the QBO or any other period, however, because the program that computes the red noise spectrum assumes the data follow a first-order Markov process. Thus it appears that any rigorous test of the significance of the quasi-biennial oscillation will have to await either the accumulation of a longer data series or the development of a more refined technique for testing the significance of peaks in spectra obtained from non-first-order linear Markovian series.

In general, the percentage of the total variance of the entire spectrum found at any given period and specific location was too small for the results to be considered of likely usefulness for long-range forecasting of seasonal sea-level pressure or possible associated weather.

The results presented in this paper do not preferentially indicate either a terrestrial or extraterrestrial origin for the observed variations of seasonal sea-level mean pressure. Whatever their ultimate cause or modus operandi may be, the forcing functions appear to act upon the atmosphere in such a way as to produce, at certain frequencies, geographically coherent patterns of enhanced spectral power that in most cases are related to major features of the seasonal mean circulation.

ACKNOWLEDGMENTS

The author is grateful for the advice and guidance received from Profs. H. C. Willett, E. N. Lorenz, and F. Sanders of the MIT Department of Meteorology when he was working on this investigation as a graduate student. The author also wishes to thank several of his colleagues in NOAA for stimulating conversations and encouragement. Mr. John T. Prohaska, formerly a research associate at the MIT Department of Meteorology is also to be thanked for the use of his computer program that printed the spectral coefficients at the grid point locations relative to the map base, thereby saving much time in plotting and analysis. Mr. Roy Topper of the Extended Forecast Division drafted the figures.

REFERENCES

Acara, A., "On Warm and Cold Years in the North Pacific Ocean," *Manuscript Report Series* No. 134, Fisheries Research Board of Canada, **1962**, 9 pp.

Angell, J. K., and Korshover, J., "Additional Evidence for Quasi-Biennial Variations in Tropospheric Parameters," *Monthly Weather Review*, Vol. 96, No. 11, Nov. **1968**, pp. 778–784.

Angell, J. K., Korshover, J., and Cotten, G. F., "Quasi-Biennial Variations in the 'Centers of Action,' " *Monthly Weather Review*, Vol. 97, No. 12, Dec. **1969**, pp. 867–872.

Bjerknes, J., "Atmospheric Teleconnections From the Equatorial Pacific," *Monthly Weather Review*, Vol. 97, No. 3, Mar. **1969**, pp. 163–172.

Brier, Glenn W., "40-Year Trends in Northern Hemisphere Surface Pressure," *Bulletin of the American Meteorological Society*, Vol. 28, No. 5, May **1947**, pp. 237–247.

Brier, Glenn W., "Long-Range Prediction of the Zonal Westerlies and Some Problems in Data Analysis," *Reviews of Geophysics*, Vol. 6, No. 4, Nov. **1968**, pp. 525–551.

Clough, Homer W., "The Two-and-a-Half Year Cycle in Weather and Solar Phenomena," *Monthly Weather Review*, Vol. 52, No. 1, Jan. **1924*a***, pp. 28–39.

Clough, Homer W., "A Systematically Varying Period With an Average Length of 28 Months in Weather and Solar Phenomena," *Monthly Weather Review*, Vol. 52, No. 9, Sept. **1924*b***, pp. 421–441.

Craig, Richard A., "Atmospheric Pressure Changes and Solar Activity," *Transactions of the New York Academy of Sciences*, Ser. II, Vol. 13, No. 7, May **1951**, pp. 280–282.

Davis, N. E., "An Optimum Summer Weather Index," *Weather*, Vol. 23, No. 8, Aug. **1968**, pp. 305–317.

DeCoster, E. M., "The Effect of the Position of the Aleutian Low on the Frequency of Lows Entering the West Coast of Canada," U.S. Weather Bureau, Extended Forecast Division, Suitland, Md., May **1945**, 4 pp. (unpublished manuscript).

Dixon, W. J., and Massey, F. J., *Introduction to Statistical Analysis*, 2d edition, McGraw-Hill Book Company, Inc., New York, **1957**, 488 pp.

Gilman, D. L., Fuglister, F. J., and Mitchell, J. M., Jr., "On the Power Spectrum of 'Red Noise,' " *Journal of the Atmospheric Sciences*, Vol. 20, No. 2, Mar. **1963**, pp. 182–184.

Granger, C. W. J., and Hatanaka, M., *Spectral Analysis of Economic Time Series*, Princeton University Press, Princeton, N.J., **1964**, 299 pp.

Holloway, J. Leith, Jr., "Smoothing and Filtering of Time Series and Space Fields," *Advances in Geophysics*, Vol. 4, Academic Press, New York, **1958**, pp. 351–390.

Klein, William H., "Principal Tracks and Mean Frequencies of Cyclones and Anticyclones in the Northern Hemisphere," *Research Paper* No. 40, U.S. Weather Bureau, Washington, D.C., **1957**, 60 pp.

Krueger, A. F., and Gray, T. I., Jr., "Long-Term Variations in Equatorial Circulation and Rainfall," *Monthly Weather Review*, Vol. 97, No. 10, Oct. **1969**, pp. 700–711.

Landsberg, H. E., Mitchell, J. M., Jr., Crutcher, H. L., and Quinlan, F. T., "Surface Signs of the Biennial Atmospheric Pulse," *Monthly Weather Review*, Vol. 91, Nos. 10–12, Oct.–Dec. **1963**, pp. 549–556.

Miller, Alvin J., Woolf, Harold M., and Teweles, Sidney, "Quasi-Biennial Cycles in Angular Momentum Transports at 500 Mb," *Journal of the Atmospheric Sciences*, Vol. 24, No. 3, May **1967**, pp. 298–304.

Mitchell, J. M., Jr., "Further Remarks on the Power Spectrum of 'Red Noise,'" *Journal of the Atmospheric Sciences*, Vol. 21, No. 4, July **1964**, p. 461.

Mitchell, J. M., Jr., "Stochastic Models of Air-Sea Interaction and Climatic Fluctuation," *Proceedings of the Symposium on the Arctic Heat Budget and Atmospheric Circulation, January 31–February 4, 1966, Rand Corporation Memorandum* RM-5233-NSF, Dec. **1966**, pp. 45–74.

Murray, R., and Moffitt, B. J., "Monthly Patterns of the Quasi-Biennial Pressure Oscillation," *Weather*, Vol. 24, No. 10, Oct. **1969**, pp. 382–389.

Namias, Jerome, "Thirty-Day Forecasting: A Review of a Ten-Year Experiment," *Meteorological Monographs*, Vol. 2, No. 6, American Meteorological Society, Boston, Mass., July **1953**, 83 pp.

Namias, Jerome, "Further Aspects of Month-to-Month Persistence in the Mid-Troposphere," *Bulletin of the American Meteorological Society*, Vol. 35, No. 3, Mar. **1954**, pp. 112–117.

Namias, Jerome, "Factors in the Initiation, Perpetuation, and Termination of Drought," *International Association of Scientific Hydrology Publication* No. 51, Helsinki, **1960**, pp. 81–94.

Namias, Jerome, "Seasonal Interactions Between the North Pacific Ocean and the Atmosphere During the 1960's," *Monthly Weather Review*, Vol. 97, No. 3, Mar. **1969**, pp. 173–192.

Nordö, Jack, "Significance of Statistical Relations Derived From Geophysical Data," *Tellus*, Vol. 18, No. 1, Feb. **1966**, pp. 39–53.

Panofsky, Hans A., and Brier, Glenn W., *Some Applications of Statistics to Meteorology*, College of Mineral Industries, The Pennsylvania State University, University Park, **1958**, 224 pp.

Reed, Richard J., "The Present Status of the 26-Month Oscillation," *Bulletin of the American Meteorological Society*, Vol. 46, No. 7, July **1965**, pp. 374–387.

Roden, Gunnar I., "On the Duration of Nonseasonal Temperature Oscillations," *Journal of the Atmospheric Sciences*, Vol. 21, No. 5, Sept. **1964**, pp. 520–528.

Roden, Gunnar I., "On the Atmospheric Pressure Oscillations Along the Pacific Coast of North America, 1873–1963," *Journal of the Atmospheric Sciences*, Vol. 22, No. 3, May **1965**, pp. 280–295.

Stark, L. Paul, "Positions of Monthly Mean Troughs and Ridges in the Northern Hemisphere, 1949–1963," *Monthly Weather Review*, Vol. 93, No. 11, Nov. **1965**, pp. 705–720.

U.S. Weather Bureau, *Daily Synoptic Series, Historical Weather Maps, Northern Hemisphere Sea Level, January 1899 to June 1939*, Washington, D.C., **1943*a***, 486 pp.

U.S. Weather Bureau, "Ten-Year Normals of Pressure Tendencies and Hourly Station Pressures for the United States," *Technical Paper* No. 1, Washington, D.C., **1943*b*** (unnumbered, mostly charts).

U.S. Weather Bureau, "Normal Weather Charts for the Northern Hemisphere," *Technical Paper* No. 21, Washington, D.C., Oct. **1952**, 74 pp.

Willett, Hurd C., "The Pattern of Solar Climatic Relationships," *Annals of the New York Academy of Science*, Vol. 95, No. 1, Oct. **1961**, pp. 89–106.

Willett, Hurd C., "Solar-Climatic Relationships in the Light of Standardized Climatic Data," *Journal of the Atmospheric Sciences*, Vol. 22, No. 2, Mar. **1965**, pp. 120–136.

Wright, P. B., "Wine Harvests in Luxembourg and the Biennial Oscillation in European Summers," *Weather*, Vol. 23, No. 8, Aug. **1968**, pp. 300–304.

[*Received March 19, 1970; revised April 29, 1970*]